HIGH-POWER EXTERNAL-CAVITY
OPTICALLY-PUMPED SEMICONDUCTOR LASERS

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TECHNICAL FIELD OF THE INVENTION

The present invention relates in general to external-cavity optically-pumped semiconductor lasers (hereinafter, OPS-lasers) including a surface-emitting, semiconductor multilayer (periodic) gain-structure. The invention relates in particular to arrangements of such lasers which can provide fundamental laser output-power of about two Watts (2.0 W) or greater, and intracavity frequency-converted arrangements of such lasers which can provide harmonic laser output-power of about one-hundred milliwatts (100 mW) or greater.

DISCUSSION OF BACKGROUND ART

The term OPS-lasers, as used herein, refers to a class of vertical-cavity surface-emitting semiconductor lasers wherein optical gain is provided by recombination of electrical carriers in very thin layers, for example, about 150 Ångstrom units (Å) or less, of a semiconductor material. These layers are generally termed quantum-well (QW) layers or active layers.

In an OPS-laser, several QW layers, for example, about fifteen, are spaced apart by separator layers also of a semiconductor material, but having a higher conduction band energy that the QW layers. This combination of active layers and separator layers may be defined as the gain-structure of the OPS-laser.

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The layers of the gain-structure are epitaxially grown. On the gain-structure is an epitaxially-grown multilayer mirror-structure, often referred to as a Bragg mirror. The combination of mirror-structure and gain-structure is referred to hereinafter as an OPS-structure.

In an (external cavity) OPS-laser, another (conventional) mirror, serving as an output-coupling mirror is spaced-apart from the OPS-structure, thereby forming a resonant cavity with the mirror-structure of the OPS-structure. The resonant cavity, accordingly, includes the gain-structure of the OPS-structure. The mirror-structure and gain-structure are arranged such that QW layers of the gain-structure are spaced apart by one half-wavelength of the fundamental laser wavelength, and correspond in position with antinodes of a standing-wave of the fundamental laser-radiation in the resonator. The fundamental-wavelength is characteristic of the composition of the QW layers.

Optical pump-radiation (pump-light) is directed into the gain-structure of the OPS-structure and is absorbed by the separator layers of the gain-structure, thereby generating electrical-carriers. The electrical-carriers are trapped in the QW layers of the gain-structure and recombine. Recombination of the electrical-carriers in the QW layers yields electromagnetic radiation of the fundamental-wavelength. This radiation circulates in the resonator and is amplified by the gain-structure thereby generating laser-radiation.

OPS-lasers have often been used in the prior art as a means of conveniently testing QW structures for later use in electrically-pumped semiconductor

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lasers. More recently, OPS-lasers have been investigated as laser-radiation sources in their own right. The emphasis of such investigation, however, appears to be on providing a compact, even monolithic, device in keeping with the generally compact nature of semiconductor lasers and packaged arrays thereof.

The gain-structure of OPS-structures may be formed from the same wide range of semiconductor-materials/substrate combinations contemplated for diode-lasers. These include, but are not limited to, InGaAsP/InP InGaAs/GaAs, AlGaAs/GaAs, InGaAsP/GaAs and InGaN/Al$_2$O$_3$, which provide relatively-broad spectra of fundamental-wavelengths in ranges, respectively, of about 960 to 1800 nanometers (nm); 850 to 1100 nm; 700 to 850 nm; 620 to 700 nm; and 425 to 550 nm. There is, of course, some overlap in the ranges. Frequency-multiplication of these fundamental-wavelengths, to the extent that it is practical, could thus provide relatively-broad spectra of radiation ranging from the yellow-green portion of the electromagnetic spectrum well into the ultraviolet portion.

In conventional solid-state lasers, fundamental-wavelengths, and, accordingly, harmonics thereof (produced by frequency-doubling or frequency-mixing) are limited to certain fixed wavelengths characteristic of a particular dopant in a particular crystalline or glassy host, for example, the well-known 1064 nm wavelength of neodymium-doped yttrium aluminum garnet (Nd:YAG). While one of these characteristic wavelengths may be adequate for a particular application, it may not be the optimum wavelength for that application.

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OPS-lasers provide a means of generating wavelengths, in a true CW mode of operation, which can closely match the optimum wavelength for many laser applications, in fields such as medicine,

5   optical metrology, optical lithography, and precision laser machining. Prior-art OPS-lasers, however, fall far short of providing adequate power for such applications. It is believed that the highest fundamental output-power that has been reported, to

10   date, for an OPS-laser is 700 mW at a wavelength of about 1000 nm (Kuznetsov, et al., IEEE Photonics Tech. Lett 9, 1063 (1997)). For an intracavity frequency-doubled OPS-laser, it is believed that highest output-power that has been reported is 6 mW

15   at a wavelength of about 488 nm (Alford et al. Technical Digest of the IEEE/OSA Conference on Advanced Solid State Lasers, Boston MA, February 1-3 1999, pp 182-184). It believed that there has been no report to date of generation of continuous wave

20   (CW) ultraviolet (UV) radiation in an OPS-laser, either directly or by frequency-multiplication.

However flexible an OPS-laser may be in potentially offering a wide selection of wavelengths, in order to be competitive in applications in which

25   solid-state and other lasers are currently used, at least an order-of-magnitude, and preferably two orders-of-magnitude increase in power over that offered by prior-art OPS-lasers is required. This power increase must also be achieved without

30   sacrifice of output-power stability and beam-quality. Further, in order to be applicable in the broadest range of applications the range of OPS-laser wavelengths available at high-power and with high beam-quality must be extended into the UV region of

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the electromagnetic spectrum, preferably to wavelengths less than 300 nm.

SUMMARY OF THE INVENTION

5   The present invention is directed to providing high-power OPS-lasers, including high-power OPS-lasers providing ultraviolet radiation, *i.e.*, at wavelengths less than about 425 nm. In one particular aspect, an OPS-laser in accordance with

10   the present invention comprises an OPS-structure having a gain-structure surmounting a mirror-structure. The gain-structure includes a plurality of active layers having pump-light-absorbing layers therebetween. The active layers have a composition

15   selected to provide emission of electromagnetic radiation at a predetermined fundamental-wavelength between about 425 nanometers and 1800 nanometers when optical-pump light is incident on the gain-structure. The mirror-structure includes a plurality of layers

20   of alternating high and low refractive index and having an optical thickness of about one-quarter wavelength of the predetermined wavelength.

        A laser-resonator is formed between the mirror-structure of the OPS-structure and a reflector spaced

25   apart therefrom. An optical arrangement is provided for delivering the pump-light to the gain-structure, thereby causing fundamental laser-radiation having the fundamental wavelength to oscillate in the laser-resonator. A heat-sink arrangement is provided for

30   cooling the OPS-structure. An optically-nonlinear crystal is located in the laser-resonator and arranged for frequency-doubling the fundamental laser-radiation, thereby providing frequency-doubled

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radiation having a wavelength half of the fundamental wavelength.

The laser-resonator, the optically nonlinear-crystal, the OPS-structure, the heat-sink arrangement and the optical pump-light-delivering arrangement are selected and arranged such that the resonator delivers the frequency-doubled radiation as output-radiation having a wavelength between about 212 nanometers and 900 nanometers at an output-power greater than about 100 milliwatts. The laser preferably has a resonator length greater than about 5.0 cm

In one embodiment of a high-power OPS-laser in accordance with the present invention, stable, single axial-mode, CW laser output-power of about 4.0 W at 488 nm wavelength is achieved by intracavity frequency-doubling 976 nm radiation from a single OPS-structure using an optically-nonlinear crystal of lithium triborate (LBO) in a resonator having a length of about twenty-five centimeters (cm). The OPS-structure has active layers of an $In_{0.18}Ga_{0.82}As$ composition, and pump-light-absorbing (separator) layers of a $GaAs_{0.978}P_{0.022}$ composition. The laser is pumped by about 34.0 W of 808 nm radiation from two diode-laser arrays. Numerical models indicate that the same resonator may be modified by including an optically-nonlinear crystal for mixing the fundamental and frequency-doubled radiation to produce about 120.0 mW of (frequency tripled or third-harmonic) 325 nm UV radiation. A simplified configuration of the resonator of this example was used without an optically nonlinear crystal to deliver fundamental output-power of about 10 W.

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The 4.0 W of frequency-doubled output-power represents over two orders-of-magnitude increase over what is believed to be the highest reported frequency-doubled output-power of any prior-art OPS-laser. It is believed that frequency-tripled output of any power has not been achieved in a prior-art OPS-laser.

Numerical models indicate that in a resonator similar to the resonator of the example above, an OPS-structure having a gain-structure $In_xGa_{1-x}P$ quantum wells with $In_yGa_{1-y}As_zP_{1-z}$ separator layers therebetween, wherein x is selected to provide fundamental radiation at 750 nm may be pumped by 12.0 Watts of pump-light at 670 nm, using a 5 mm-long LBO crystal for frequency doubling to provide output-power in excess of 1 Watt at the frequency-doubled wavelength of 375 nm.

This remarkable increase in OPS-laser output-power and the ability to generate high, CW, UV output-power, either by frequency-doubling or frequency-tripling, is achieved without sacrifice of beam-quality. Single mode operation provides that OPS-lasers in accordance with the present invention can have a beam quality less than 2.0 times, and as low as 1.2 times the diffraction limit. This high-beam quality makes the inventive OPS-lasers ideal for applications in which the output radiation must be focused to a very small spot for making precise incisions in inorganic or organic material, or must be efficiently coupled into an optical fiber for transport to a location where it is to be used.

In another aspect of an OPS-laser in accordance with the present invention, the laser includes first and second resonators arranged such that a portion of

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the resonator axes of each are on a coaxial path. The first resonator includes an OPS-structure arranged outside the coaxial path to provide a selected fundamental-wavelength of laser radiation.

5 Located on the coaxial path of the first and second resonators is an optically-nonlinear crystal arranged for frequency-doubling the fundamental radiation. The first and second resonators are interferometrically matched to maintain optimum

10 phase-matching between fundamental and frequency-doubled radiation in the optically-nonlinear crystal. Fundamental-wavelength radiation and frequency-doubled radiation circulate together only along the coaxial path. An optically-nonlinear crystal is

15 located in the second resonator outside the coaxial path for doubling the frequency of the frequency-doubled radiation thereby providing frequency-quadrupled radiation. Numerical models indicate that by using the 976 nm OPS-structure and pumping

20 arrangement of the above-described first embodiment, this second embodiment is capable of providing about 2.0 W of frequency-quadrupled (244 nm) radiation.

In yet another aspect of an OPS-laser in accordance with the present invention, the laser

25 includes first and second interferometrically-matched resonators arranged such that a portion of the resonator axes are on a coaxial path. The coaxial path includes a first optically-nonlinear crystal arranged for frequency-doubling as discussed above

30 with respect to the second embodiment. Fundamental-wavelength radiation and frequency-doubled radiation circulate together only along the coaxial path. A second optically-nonlinear crystal is located in the coaxial path of the first and second resonators for

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mixing the fundamental radiation with frequency-doubled radiation thereby providing frequency-tripled radiation. Numerical models indicate that by using the 976 nm OPS-structure and pumping arrangement of

5   the above-described first embodiment, this third embodiment is capable of providing about 4.0 W of frequency-tripled (325 nm) radiation.

Other, more general, aspects of OPS-lasers in accordance with the present invention include but are

10   not limited to: design of heat-sink configurations and bonding methods for cooling an OPS-structure which allow the above exemplified high pump-powers to be directed on the OPS-structure while maintaining a safe operating temperature therefor; design of

15   optically-long resonators for providing a relatively large fundamental mode-size at OPS-structure to take advantage of a larger pumped-area, thereby increasing laser output-power; design of specific, folded-resonator configurations for optimizing output of

20   frequency-converted radiation and preventing reflection of the frequency-converted radiation back into the OPS-structure where it would be lost through absorption; selection of a specific ratio of pumped area to mode-size at the OPS to optimize use of gain,

25   and to prevent generation of transverse modes of oscillation; use of an intracavity wavelength-selective element for preventing oscillation of fundamental radiation at wavelengths outside the spectral range of acceptance of optically nonlinear

30   crystals; selection of optically nonlinear materials for maximum spectral acceptance to allow the use of efficient and tolerant wavelength-selective devices for the former; configuration of OPS-structures to eliminate parasitic lateral oscillation which would

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otherwise reduce output power; design of OPS-structures for minimum net stress and reliability under high power operation; use of radial-index gradient lens to optimize multiple optical-fiber delivery of pump-light; and design of mirror-structures for the inventive OPS-structure for maximum thermal-conductivity thereby facilitating cooling of the OPS-structures.

It will be particularly evident from the detailed description of the present invention presented below that for achieving the high powers discussed above, OPS-laser resonators in accordance with the present invention depart radically from the "compactness" philosophy of prior-art OPS-lasers and are inventively configured for intracavity frequency multiplication. It will also be evident that significant attention is directed to thermal management of OPS-structures, to the design of OPS-structures themselves, and to selection of frequency multiplication materials, in order to achieve the remarkable output-power levels, and stability of the inventive OPS-lasers. It will further be evident that certain inventive aspects of the invention are applicable to both high and low-power OPS-lasers, or even to laser types other than OPS-lasers.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and constitute a part of the specification, schematically illustrate a preferred embodiment of the present invention, and together with the general description given above and the detailed description of the preferred embodiment

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given below, serve to explain the principles of the invention.

FIG. 1 schematically illustrates a preferred embodiment of an OPS-laser in accordance with the present invention having a resonator including an OPS-structure and an optically-nonlinear crystal arranged for intracavity frequency-doubling the fundamental-wavelength of the OPS-structure.

FIG. 2 is a graphical representation of the mode-size of fundamental radiation as function of axial position in the resonator of FIG. 1

FIG. 3 schematically illustrates details of one preferred arrangement and composition of semiconductor layers in the OPS-structure of FIG. 1.

FIG. 4. schematically illustrates another preferred embodiment of an OPS-laser in accordance with the present invention having a resonator including an OPS-structure and two optically-nonlinear crystals arranged for intracavity frequency-tripling the fundamental-wavelength of the OPS-structure.

FIG. 5. schematically illustrates yet another preferred embodiment of an OPS-laser in accordance with the present invention having a first resonator including an OPS-structure and a second resonator having a common optical path with the first resonator, the common optical path of the resonators including two optically-nonlinear crystals arranged

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for intracavity frequency-tripling the fundamental-
wavelength of the OPS-structure.

FIG. 6 schematically illustrates still another
preferred embodiment of an OPS-laser in accordance
5   with the present invention having a first resonator
including an OPS-structure and a second resonator
having a common optical path with the first
resonator, the resonators being arranged for
intracavity frequency-quadrupling the fundamental-
10   wavelength of the OPS-structure.

FIG. 7 schematically illustrates a further
preferred embodiment of an OPS-laser in accordance
with the present invention having a straight
resonator including an OPS-structure and a
15   birefringent filter.

FIG. 8 schematically illustrates the OPS-
structure of any of FIGS 1 and 4-7 bonded to a heat-
sink assembly in accordance with the present
invention.

20   FIG. 9 is a graph depicting isothermal contours
produced by uniform heat-flow into a selected area of
a surface of a relatively-massive copper heat-sink.

FIG. 10 is a graph depicting isothermal contours
produced by uniform heat-flow into the selected area
25   of FIG. 7 on a surface of a CVD-diamond layer bonded
to a relatively-massive copper heat-sink.

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FIG. 11 is a perspective view schematically illustrating parasitic lateral oscillation in an OPS-structure in accordance with the present invention.

FIG. 12 is a graph schematically illustrating computed conversion efficiency as a function of wavelength for LBO and potassium niobate ($KNbO_3$) crystals of equal-length.

FIG. 13 schematically illustrates a further preferred embodiment of an OPS-laser in accordance with the present invention having a resonator including two OPS-structures and an optically-nonlinear crystal arranged for intracavity frequency-doubling the fundamental-wavelength of the OPS-structure.

FIG. 14 schematically illustrates a further preferred embodiment of an OPS-laser in accordance with the present invention having a folded resonator terminated by first and second external mirrors and being folded by a mirror-structure of an OPS-structure.

DETAILED DESCRIPTION OF THE INVENTION

Turning now to the drawings, wherein like components are designated by like reference numerals. FIG. 1 schematically illustrates an OPS-laser 20 in accordance with the present invention. Laser 20 includes a resonator 22 having a longitudinal axis 24 thereof folded by a fold-mirror 26. Resonator 22 is terminated at one end thereof by a flat mirror or reflector 28, and at the other end thereof by a mirror portion (mirror-structure) 30 of an OPS-

structure 32. A gain portion (gain-structure) 34 of OPS-structure 32 is thus located in the resonator in contact with a resonator mirror, *i.e.*, mirror-structure 30.

5   Gain-structure 34 of OPS-structure 32 is an epitaxially-grown monolithic semiconductor (surface-emitting) multilayer structure including a plurality of active layers (not shown in FIG. 1) spaced apart by pump-light-absorbing separator-layers (also not

10   shown in FIG. 1). It should be noted here that the terminology "spaced apart by pump-light-absorbing separator layers" in the context of this description and the appended claims does not preclude there being other layers between the QW layers. Depending on the

15   composition of the QW layers, one or more other layers may be included for strain-management, carrier-confinement and the like. Any such arrangement is applicable in the context of the present invention.

20   In prior-art OPS-lasers, the mirror-structure of the OPS-structure is typically also an epitaxially-grown multilayer structure grown from different compositions of material having a general composition $Al_xGa_{(1-x)}As$ (abbreviated AlGaAs), wherein increasing x

25   increases the bandgap of the material, and lowers the refractive index. While this is one form of mirror-structure which could be used for mirror-structure 30, it is neither the only form contemplated, nor the preferred form contemplated. Mirror-structure 30 in

30   an OPS-structure 32 in accordance with the present invention, need not be epitaxially grown and may include dielectric or metal layers. If epitaxially grown, it need not be formed entirely from materials in the (ternary) AlGaAs system. Preferred mirror-

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structures are discussed in detail further
hereinbelow.

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Continuing now with reference to FIG. 1, OPS-
structure 32 is bonded in thermal contact with a
heat-sink 36. Heat-sink 36 is preferably an
actively-cooled heat-sink such as a microchannel-
cooler. A particularly preferred arrangement of heat
sink 36 is discussed in detail further hereinbelow.

OPS-structure 32 is optically pumped,
preferably, by pump-light delivered from one or more
diode-laser arrays (not shown). In FIG. 1, pump-
light is delivered from two diode-laser arrays via
two optical fibers (or fiber bundles) 40. Pump-light
42 diverges as it exits a fiber 40. In each case,
the diverging pump-light is directed by a mirror 44,
through focusing lenses 46 and 48, to be focused
(only an axial ray shown) on gain-structure 34 of
OPS-structure 32. It should be noted, that while two
pump-light-delivery fibers 40 and associated
focussing optics are illustrated in FIG. 1, this
should not be considered as limiting the present
invention. Only one, or more than two pump-light-
delivery fibers and associated focusing-optics may be
used, and even different pump-light sources with or
without fiber delivery may be used, without departing
from the spirit and scope of the present invention.
Further it should be noted that optical fibers and
fiber bundles are just one preferred means of
transporting pump-light from a source thereof. Other
forms of what may be generally termed "a lightguide",
for example, solid or hollow light-waveguides maybe
used without departing from the spirit and scope of
the present invention.

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Mirrors 26 and 28, and mirror-structure 30 of OPS-structure 32, each have maximum reflectivity at a fundamental (emission) wavelength characteristic of the composition of (active layers of) gain-structure

5   34 of OPS-structure 32. Energizing gain-structure 34 of OPS-structure 32 causes laser radiation having the fundamental-wavelength (fundamental-radiation) to circulate in resonator 22. This fundamental-radiation is indicated in FIG. 1 by single arrows F.

10   Included in resonator 22, in folded portion 22A thereof, proximate, but spaced apart from mirror 28, is an optically-nonlinear crystal 50 arranged for frequency-doubling (halving the wavelength of) the fundamental radiation. This generates frequency-

15   doubled or second-harmonic (2H) radiation indicated in FIG. 1 by double arrows 2H. 2H-radiation is generated both on a first pass of fundamental laser radiation therethrough and on a return pass of the fundamental-radiation after it is reflected from

20   mirror 28. Fold-mirror 26 is transparent to the 2H-radiation and, accordingly, serves to couple the 2H-radiation out of resonator 22.

It should be noted here, that this folded-resonator arrangement of an OPS-laser in accordance

25   with the present invention is particularly important, considering the high-power operation of the device. The folded-resonator arrangement allows formation a resonating beam in resonator 22 having optimum characteristics at OPS-structure 32 and at the

30   optically-nonlinear crystal 50. In one arrangement the pump-light spot-size at OPS-structure 32 preferably has a gaussian shape, preferably with a $1/e^2$ radius of about 230 micrometers (μm). In order to maximize overlap and obtain optimum power-

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extraction in fundamental transverse mode, the resonating fundamental-radiation at OPS-structure 32 preferably has a similar size of 230 μm (1/e^2 radius). Extensive numerical simulations, corroborated by experimental results, indicate that the spot-size of fundamental-radiation in optically-nonlinear crystal 50 is preferably of the order of 50 μm (1/e^2 radius) for optimum second harmonic generation. FIG. 2 depicts mode-size (radius) as a function of axial position within resonator 22 of laser 20. of FIG. 1. It can be seen that this preferred resonator arrangement of plane end mirrors (mirror-structure 30 and external mirror 28) folded by a concave fold-mirror 26 (here, having a radius of 100 mm), provides above-discussed preferred spot or mode-sizes at OPS-structure 32 and in optically-nonlinear crystal 50. The folded-resonator arrangement, as noted above, also allows two passes of fundamental radiation through optically-nonlinear crystal 50, thereby increasing the amount of 2H-radiation generated. Extraction of the 2H-radiation via fold-mirror 36 prevents 2H-radiation from being lost by absorption in OPS-structure 32.

In an intracavity frequency-doubled laser in accordance with the present invention, it is preferable to include a wavelength-selective element, such as a birefringent filter or an etalon in the resonator for forcing the resonator to oscillate precisely at the wavelength that the optically-nonlinear crystal is arranged to frequency-double. This is discussed in detail further hereinbelow with respect to selection of a preferred material for optically-nonlinear crystal 50. In laser 20, such a wavelength-selective element is depicted in the form

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of a birefringent filter 52 arranged at Brewster's
angle (here 57.1°) to axis 24 of resonator 20. It is
emphasized here that the purpose of this wavelength-
selective element is not axial-mode selection, as

5 this is accomplished by a combination of the unique
properties of OPS-structure 32 combined with its
location in resonator 22. Rather, birefringent
filter 52 is used to effectively spectrally narrow
the gain-bandwidth of gain-structure 34 of OPS-

10 structure 32 to a bandwidth narrower than a spectral
acceptance region over which the optically-nonlinear
crystal 50 is effective. This prevents laser 20 from
oscillating at wavelengths where the optically-
nonlinear crystal is ineffective. This aspect of

15 OPS-lasers in accordance with the present invention
is also discussed in detail further hereinbelow.

In one example of a laser 20 in accordance with
the arrangement of FIG. 1, OPS-structure 32 (see FIG.
3) has a gain-structure 34 comprising fifteen QW or

20 active-layers of an $In_{0.18}Ga_{0.82}As$ composition, having a
thickness of about 75.0 Angstrom Units (Å) providing
a nominal fundamental (emission) wavelength of 976
nm. Between the QW layers are pump-light-absorbing
(separator) layers of a $GaAs_{0.978}P_{0.022}$ composition

25 having a thickness of 1217 Å. Between the QW layers
and the separator layers is a strain-relieving layer
of GaAs having a thickness of about 50 Å. Mirror-
structure 30 comprises 27 pairs or periods of
alternating layers of GaAs having a refractive index

30 of about 3.51 and $AlAs_{0.96}P_{0.04}$ having a refractive
index of about 2.94 and an optical thickness of one-
quarter wavelength at the fundamental-wavelength.
Gain-structure 34 also includes a carrier-confinement
layer of $Ga_{0.51}In_{0.49}P$, having a thickness of 1588Å,

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between the last separator layer and mirror-structure 30. At an opposite extremity of gain-structure 34 there is also a carrier-confinement layer of $Ga_{0.51}In_{0.49}P$ having a thickness of 1588Å.

5   OPS-structure 32 is epitaxially grown on an n-type GaAs wafer (substrate), gain-structure 34 being grown first, beginning with the carrier confinement layer. Mirror-structure 30 is epitaxially-grown on the gain-structure. After the OPS-structure is

10   grown, the wafer is etched away. The first-grown confinement layer serves as an etch-stop layer when the substrate is removed by etching. The wafer, and structures grown thereon, is diced into several OPS-structures 32 in the form of square "chips" about 2.0

15   mm by 2.0 mm.

An OPS-structure (chip) is first bonded to a microchannel-cooler (cooler 36). One preferred microchannel-cooler is a Model SA-2, available from Saddleback Aerospace Corporation of Los Alamitos,

20   California. Before bonding the OPS-structure to the microchannel-cooler, a relatively thin (about 0.3 mm thick) synthetic diamond (CVD-diamond) layer, is bonded to the microchannel-cooler. The synthetic diamond layer has a particular thermal-management

25   function which is discussed in further detail hereinbelow.

In prior-art methods for bonding to diamond a gold overcoated platinum metalization is applied to the diamond before bonding. Indium is solder used

30   for bonding. Under the operating conditions contemplated for a bonded OPS-structure in accordance with the present invention, the gold overcoating can dissolve in the indium bonding material, eventually causing long-term instability of the bonded joint,

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with an associated deformation of the OPS structure.
One preferred bonding method in accordance with the
present invention which is believed may provide
superior long-term stability and avoid potential
5   deformation is to provide metalization on the diamond
comprising a titanium layer overcoated by a platinum
layer only without a gold overcoating. Bonding is
then performed using indium solder. It is believed
that such a bonding method would be superior to
10   prior-art chip-bonding methods, not only under the
high-power operating conditions contemplated for OPS-
lasers in accordance with the present invention but
for any OPS-laser.

Another possible bonding method would be to use
15   a more stable, gold-tin eutectic solder rather than
indium solder. It is possible, here, however, that a
coefficient of thermal expansion (CTE) mismatch with
diamond may limit its use with diamond heat-sinks.
The CTE mismatch problem may be avoided by use of
20   alternate heat-sink materials having a closer CTE
match to the gold-tin eutectic, such as copper-
tungsten (Cu-W), cubic boron nitride, silicon-diamond
composite, and the like. Some compromise in output-
power performance may be expected here, however, due
25   to the lesser heat conduction efficiency of these
materials compared to diamond. The CTE mismatch
problem becomes greater the larger the chip.

After the OPS-structure is bonded to the
diamond-layer/microchannel-cooler, the GaAs substrate
30   is removed by etching. Preferably, an antireflection
coating is deposited on thus-exposed gain-structure
34 to improve entry of pump-light into the gain-
structure.

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Regarding optical pumping of OPS-structure 32, each fiber 40 delivers about 17.0 W of 795 nm radiation from a FAP-30C-800-B diode-laser-array package available from Coherent Semiconductor Group

5 of Santa Clara, CA.   Mirrors 44 are dielectric-coated mirrors having greater than 99.9% reflectivity at 795 nm and 28° angle of incidence. Lenses 46 are cemented doublets having a focal length of 40.0 mm and a diameter of 18.0 mm.   Lenses 48 are cemented

10 doublets having a focal length of 21.0 mm and a diameter of 14 mm . These lenses are available from Melles Griot of Irvine, California. The pump-light is focused by the mirrors and lenses into an area of OPS-structure. A total of 34 Watts of pump-light in

15 the pumped area has a substantially Gaussian intensity profile with a radius of about 260 μm at the $1/e^2$ points. The exemplified diode-laser-array packages providing the pump-light require about 50.0 Watts each of so-called "wallplug" electrical-power

20 input generate 20.0 Watts of pump radiation coupled into transport fibers 40.

Birefringent filter 52 is quartz plate having a thickness of 3.08 mm and oriented as depicted in FIG. 1 at 57.1 degrees to axis 24, with the quartz optical

25 axis in the plane of the plate. Such a filter is available as Part No. BF254-6T from VLOC Company of Port Richey, Florida. This orientation of birefringent filter 52 provides that fundamental radiation F is polarized perpendicular to the plane

30 of FIG. 1 as illustrated by arrow P1.

Birefringent filter 52 has narrow transmission-peaks separated by about 35 nm, each with a full width at half maximum transmission (FWHM) of about 3 nm. Maximum selectivity is achieved by keeping the

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quartz optic-axis at an angle of about 45 degrees from an axis defined by the intersection of the vertical plane with the plane of the plate. The wavelength of the transmission peaks can be shifted

5 by rotating the plate slightly around an axis normal to its faces, thus achieving tuning of the filter. The computed tuning rate, confirmed experimentally, is about 5.6 nm per degree of rotation

Mirror 28 is a plane mirror and fold-mirror 26

10 is a concave mirror having a radius of curvature of 100 mm. Mirrors 26 and 30 are axially separated by a distance of 202 mm. Mirrors 26 and 28 are axially separated by a distance of 56 mm. Accordingly, resonator 22 has an axial length of 258 mm (25.8 cm).

15 Optically nonlinear crystal 50 is a 5 mm-long crystal of lithium triborate (LBO) having a cross-section of 3 mm x 3 mm. The crystal is cut for type-1 phase matching for 976 nm radiation. Propagation of the fundamental beam is in the

20 crystallographic X-Y plane. The propagation direction is at an angle of 17.1 degrees from the X-axis. The fundamental-radiation is polarized perpendicular to the X-Y plane (parallel to the Z-axis). Second-harmonic radiation is polarized in

25 the X-Y plane, as illustrated by arrow P2.

The above-specified exemplary OPS-laser generated an intracavity power of fundamental (976 nm) radiation of about 300 watts yielding frequency-doubled (488 nm) radiation at an output power of 5

30 Watts in single longitudinal (axial) mode and single transverse mode. The beam divergence was measured at 1.2 times the diffraction limit ($M^2 = 1.2$). The quantity M^2 is a numerical measure which represents a ratio of the size of the beam to a diffraction-

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limited size. A high quality beam may be regarded as a beam having an M^2 of about 2.0 or less. The high-beam quality available with the inventive OPS-lasers make them useful for applications in which the laser

5   output-radiation must be focused to a very small spot for making precise incisions in inorganic or organic material, or must be efficiently coupled into an optical-fiber or guided by an articulated arm for transport to a location where it is to be used.

10   From the power point-of-view alone, this represents about a one-thousand-fold increase over the above-discussed 6.0 mW output of a prior-art IC, frequency-doubled OPS-laser. Surprisingly, the fundamental radiation, and, accordingly, the

15   frequency-doubled radiation was in a single axial (longitudinal) mode. Temporal stability of the output-radiation is estimated in terms of output-fluctuation or noise of less than about 0.05% RMS over a band DC to 10 MHz. It is believed that in

20   other embodiments OPS-lasers in accordance with the present invention described hereinbelow a noise of less than about 0.1% can be obtained. Pump-light to second-harmonic efficiency is about ten percent. Electrical to second-harmonic efficiency is about

25   four percent. Generally, a pump-light to second-harmonic efficiency of 3.0 percent or greater may be achieved in appropriate embodiments of inventive OPS-lasers discussed herein.

      Detuning of the cavity (moving mirror 28 axially

30   away from fold-mirror 36) to reduce the beam spot-size at OPS-structure 32, forced operation in multiple transverse mode, allowed obtaining up to 7.5 Watts of output-power at 488 nm, thereby obtaining even higher power and efficiency at the expense of a

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reduced beam-quality due to the multiple mode operation. The relationship of mode-size to pumped-area (pump-spot size) in connection with ensuring single axial-mode operation is discussed in detail further hereinbelow.

The high output-power at 488 nm of the inventive IC double OPS-laser is obtained with a total input electrical-power to the pump-light-providing diodes of about 100 Watts. In prior-art lasers, multi-Watt, high-beam-quality radiation at 488 nm was only obtainable as the output of argon ion (gas) lasers. These lasers typically require several thousands of Watts (up to 30 Kilowatts) of electrical-power input. Accordingly, the above-exemplified laser in accordance with the present invention provides an improvement in the "electrical-to-optical" efficiency of two orders of magnitude for 488 nm lasers.

Continuing now with the description of preferred embodiments of OPS-lasers in accordance with the present invention, an important aspect of the above-discussed example of an OPS-laser is the discovery that such a high-fundamental power can be generated from an OPS-structure, by paying attention, inter alia, to thermal management of the intensely-pumped OPS-structure in combination with increasing the dimensions of the resonator well beyond those of prior-art OPS-lasers.

Having established experimentally that such a high fundamental and 2H-power can be provided, it is possible to numerically-model other inventive OPS-lasers based on the same or different OPS-structures 32 and "long resonator" arrangements, similar to that of laser 20, which generate other fundamental and 2H wavelengths at similar output power.

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In particular, high-power CW radiation in the ultraviolet spectral region, for example, at about 375 nm, can be generated by using an OPS-structure 32 having a gain-structure 34 having $In_xGa_{1-x}P$ quantum wells with $In_yGa_{1-y}As_zP_{1-z}$ separator layers therebetween. Such an OPS-structure, pumped with 670 nm radiation from fiber-coupled diode-lasers (for example, SDL part number 7470 P-5 from SDL, Inc., of San Jose, CA) provides gain at 750 nm. A resonator similar to resonator 22 of FIG. 1 may be used, with a similar birefringent filter 52, suitably angle-tuned, and with an optically-nonlinear crystal 50 of LBO arranged for frequency doubling the 750 nm radiation. In this regard, the LBO crystal is preferably cut for propagation in the X-Y crystallographic plane, at an angle of 37.5 degrees from the X-axis. The polarizations of the fundamental and 2H-radiation are the same as for the (976 nm fundamental-wavelength) laser 20 exemplified above.

The efficiency of conversion for 750 nm radiation for the LBO crystal is computed to be slightly higher (17% higher) than the efficiency of conversion for 976 nm radiation for equal lengths of the optically-nonlinear crystal. This results from a balancing of two opposing factors. The effective nonlinearity (nonlinear-coefficient) of LBO at 750 nm is lower, at about 1.0 picometer per volt (pm/V) compared with a value of 1.2 pm/V at 975 nm, due to the different angle of propagation. The overall conversion-efficiency, however, is proportional to the square of the nonlinear-coefficient, but is also proportional to the inverse of the square of the wavelength. Accordingly, the shorter wavelength (750

nm), is instrumental in providing the above-discussed improvement of the overall conversion-efficiency.

In one numerically-simulated example of a frequency-doubled, 750 nm fundamental-wavelength laser 20, 12.0 Watts of pump-light at 670 nm, obtained from 4 fiber-coupled diode-laser arrays or modules, using a 5 mm-long LBO crystal for optically-nonlinear crystal 20, resulted in computed output-power in excess of 1 Watt at the 2H-wavelength of 375 nm. Using higher pump-power from more the same number of more-powerful diode-laser arrays, or from more arrays of the same power, can provide 375 nm output-power comparable to the 488 nm output power exemplified above for the same resonator. Use of more pump-light arrays is possible using an alternative pump-light delivery arrangement discussed in detail further hereinbelow.

Having established experimentally, and numerically corroborated, that such a high fundamental power can be generated, it is possible to configure other "long-resonator" type, inventive OPS-lasers based on the same OPS-structures, for generating third harmonic (3H) and fourth harmonic (4H) radiation, and to compute, with confidence, what output-power can be generated at such third and fourth harmonic-wavelengths in the UV region of the electromagnetic spectrum. Descriptions of such resonator configurations are set forth below, exemplifying generation of the third harmonic of 750 nm radiation, and the fourth harmonic of 976 nm radiation.

Referring now to FIG. 4, a laser 60 including a resonator 23 is schematically illustrated. Laser 60 is identical in most regards to laser 20 of FIG. 1,

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with the following exceptions. Mirror 28 is coated for high reflectivity at the fundamental and second (2H) harmonic wavelengths. Mirror 26 is maximally reflective at the fundamental-wavelength and highly transmissive at the 2H and 3H-wavelengths. An optically-nonlinear crystal 62, is located between optically-nonlinear crystal 50 and mirror 26 in folded arm 23A of resonator 23. Optically-nonlinear crystal 62 is arranged to mix the fundamental and 2H wavelengths (frequencies), thereby generating frequency-tripled radiation, indicated in FIG. 4 by triple arrows 3H. Both 2H and 3H-radiation leave resonator 23 via fold-mirror 26. The 2H and 3H-radiations are then separated by a dichroic beamsplitter 64.

Now, third-harmonic generation (mixing of fundamental and 2H frequencies) is known to be proportional (dependent on optically-nonlinear crystal characteristics) to the product of the fundamental and second-harmonic power. So, based on experimentally established values for these powers in this resonator, and on documented values for 3H-generation efficiency of various optically-nonlinear materials, it can be predicted with a high degree of confidence that the above-described example of a laser 60 using β-barium borate (BBO) for optically-nonlinear crystal 62 can generate about 150 mW of true-CW, single-mode, laser output-power at a wavelength of 250 nm, assuming an intracavity fundamental power of about 300 W at 750 nm generating about 5.0 W of 2H-radiation (375 nm).

A BBO crystal (crystal 62) suitable for this process is cut for propagation at an angle of 48 degrees from the optic axis, in a plane containing

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the optic (Z) axis and making an angle of 30 degrees
with the X-Z crystallographic plane. Fundamental-
radiation and 2H-radiation propagate with
polarization perpendicular to the optic axis,
5   (ordinary polarization). The 3H-radiation is
generated with extraordinary polarization (normal to
the fundamental polarization).

Computations based on published data from
crystal manufacturers (CASIX) indicate that by
10   focussing 300 watts of 750 nm radiation down to a
radius of 60 μm in optically-nonlinear crystal 62 (in
arm 20A of resonator 20), together with 5 Watts of
2H-radiation (375 nm) focused coaxially in the same
crystal to a radius of 50 nm, about 150 mW of 250 nm
15   (3H) radiation is generated. The above-described BBO
crystal employs type-I phase matching. This means
that the fundamental and the 2H radiation must have
the same polarization within the crystal.

The second-harmonic-generating LBO crystal
20   (optically-nonlinear crystal 50), however, generates
2H-radiation with polarization orthogonal to the
polarization of the fundamental-radiation. The
polarization of the 2H-radiation, accordingly, must
be rotated by 90 degrees before it enters optically-
25   nonlinear crystal 62. This may be achieved by a
birefringent quartz plate (polarization rotator) of
such design that it has retardation of an even
integer multiple of π for the fundamental radiation,
and retardation of an odd integer multiple of π for
30   the 2H radiation.

Such a polarization-rotator (depicted in FIG. 4
in phantom as polarization-rotator 65) is inserted in
the common path (arm 20A) of the fundamental and 2H-
radiation between optically nonlinear crystals 50 and

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62.   Polarization-rotator 65, leaves the polarization
of the fundamental-radiation unaltered, and rotates
the linear polarization of the 2H-radiation by an
amount equal to twice the angle between the initial
5   polarization and the direction of the optic-axis of
the retardation plate.

As an alternative, a BBO crystal may be cut for
type-II mixing, so that polarization-rotator 65 is
not required to modify the polarization of the 2H-
10 radiation. Conversion in this case, however, can be
expected to be less efficient.

Providing a resonator mirror or reflector on any
optically nonlinear crystal in a OPS-laser resonator
in accordance with the present invention is not
15 precluded. However, additional measures such as
temperature control of the crystal may be required to
resolve the conflicting alignment requirements for
the resonator and the cyrstal.

In resonator 23 of FIG. 4, third-harmonic
20 generation from 970 nm fundamental-radiation is also
possible using the alternatives discussed above for
750 nm fundamental radiation. Numerical simulations
indicate that such third-harmonic generation could
generate about 150 mW of 325 nm radiation. Those
25 skilled in the art, from the above discussed example
can determine appropriate nonlinear crystal
parameters without further detailed description.
Accordingly, no such detailed description is
presented herein.

30   The 150 mW of third-harmonic radiation
exemplified above represents more than a twenty-times
increase in power on third-harmonic generation over
the maximum believed to have been reported in the
prior art for only second-harmonic generation. The

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arrangement for generating this third harmonic
radiation represented by laser 60, however, is
arguably a somewhat inefficient approach to IC
generation of third harmonic radiation. Significant
5   improvements in harmonic output-power are possible in
another family of OPS-laser resonators in accordance
for the present invention discussed below, beginning
with reference to FIG. 5

        In FIG. 5, yet another embodiment 70 of an OPS-
10   laser in accordance with the present invention is
schematically depicted. Laser 70 includes two
resonators 25 and 27 having a common, axial path 35
(indicated in bold line in FIG. 5) over a portion of
their total length. Resonator 25 may be defined as a
15   "fundamental resonator" and is terminated at one end
thereof by mirror 28 and at the other end thereof by
mirror-structure 30 of OPS-structure 32. Resonator
25 is folded by a fold-mirror 26. OPS-structure 32
is mounted and pumped as described above for lasers
20   20, and 60. Only one pump-light-delivery fiber and
associated focussing optics are depicted in FIG. 5,
for clarity.

        Resonator 27 may be defined as a "second-
harmonic resonator". It is used to build up 2H-
25   radiation to levels much higher than are achieved in
the simple double-pass arrangements of above-
described resonators 22 and 23. Resonator 27 is
terminated at one end thereof by mirror 28 and at the
other end thereof by a mirror 74. Resonator 27 is
30   also folded by a fold-mirror 26. Fold-mirror 26 in
this embodiment is coated for maximum reflection at
the fundamental and 2H-wavelengths and maximum
transmission at the 3H-wavelength. Mirror 28 in this
embodiment is coated for maximum reflection at the

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fundamental, 2H and 3H-wavelengths. The axes of the
resonators are folded together by a dichroic
beamsplitter 72 coated for maximum reflection at the
2H-wavelength and maximum transmission at the
5   fundamental-wavelength. Accordingly, the common
(here, folded) axial path of resonators 25 and 27
extends between beamsplitter 72 and mirror 28. It is
pointed out here, that all coatings mentioned above
are believed to be within the capabilities of
10   commercial suppliers of optical coating services.
One such supplier is Coherent Auburn Group, of
Auburn, California.

Located in the common axial-path of resonators
27 and 27, proximate beamsplitter 72, is an
15   optically-nonlinear crystal 50 arranged for doubling
the fundamental-wavelength. The 2H-radiation
generated by the frequency-doubling circulates and
builds up in resonator 27, thereby greatly increasing
the amount of intracavity 2H-radiation compared with
20   the simple "double-pass" arrangement of laser 20 of
FIG. 1. Located in common, folded portion 27A of
resonators 25 and 27, (wherein, of course, both
fundamental and 2H-radiation are circulating) is an
optically-nonlinear crystal 62 arranged for mixing
25   the fundamental and 2H-radiation to generate 3H-
radiation. 3H-radiation so generated escapes the
resonators via fold-mirror 26. Regarding the
resonators in general, the following should be noted.

It is preferable that resonators 25 and 27 have
30   about the same length and are similarly optically
configured. This provides that the mode-size for
fundamental and 2H-radiation is about the same,
thereby maximizing mixing efficiency. It is also
preferable that the resonators are

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interferometrically-matched to maintain an optimum phase-relationship between the circulating fundamental and 2H-radiation at the location of optically-nonlinear crystal 50. This is required to ensure that 2H-radiation generated in optically-nonlinear crystal 50 is added, in phase, to the 2H-radiation circulating in the 2H-resonator. This ensures that circulating 2H-radiation can grow to high levels, thereby providing a high conversion-efficiency in the BBO mixing-crystal (optically nonlinear crystal 62). In this regard, it is also preferable that fundamental resonator 25 operate in only a single axial-mode to avoid loss of power from mode-competition. Conditions for providing single axial-mode operation are discussed in detail further hereinbelow.

One arrangement for providing interferometric-matching of the resonators is to provide an axial driver 76, such as a piezo-electric driver, for mirror 74 of resonator 27. As mirror 74 is axially-driven, circulating 2H-radiation rises to a maximum level and falls to a minimum level (which may be zero or near-zero) corresponding respectively to a maximally-in-phase condition and a maximally-out-of-phase condition at optically-nonlinear crystal 50 for the fundamental and 2H-radiation (standing waves). Correspondingly, 3H-output-power would rise and fall. A beamsplitter 78 directs a small sample-fraction 3HS of the 3H-output to a detector 80. Detector 80 is cooperative with a controller 82 which adjusts driver 76 to maintain peak output-power.

As noted above, third-harmonic generation is proportional to the product of the fundamental and second-harmonic power. By incorporating a second

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resonator for 2H-power, laser 70 provides that a much greater 2H-power is available for mixing than is the case in laser 60 of FIG. 4, and, further, without any increase being required in the fundamental-power.

5   So, based on above-discussed values for available fundamental-powers in this resonator and documented values for 2H-generation efficiency of LBO it can be numerically determined that 300 W of circulating 750 nm radiation would generate about 200 W of

10   circulating 375 nm radiation in resonator 27. The double-pass combination of these in an optically non-linear crystal 62 of β-barium BBO can generate about 4 W of true-CW, single-mode, laser output-power at a wavelength of 250 nm. Similar output-power levels

15   for 325 nm radiation can be determined for 3H-conversion of 976 nm radiation. This is a more than a six-hundred-times increase in power on third-harmonic generation over the maximum believed to have been reported for only second harmonic generation in

20   prior-art OPS-lasers.

An optically-nonlinear (mixing) crystal preferable for laser 70 is the same as that discussed above with reference to laser 60. Care should be exercised in the design of resonator 25 of laser 70,

25   however, in particular concerning the sizes of the beams within the optically-nonlinear crystals 50 and 62.

The fundamental and 2H-beams are preferably focused tightly in optically nonlinear crystal 62 to

30   maximize conversion (mixing) efficiency. An optimum range of larger beam sizes, however, is preferred for fundamental-radiation in optically-nonlinear (doubling) crystal 50. Extensive numerical modeling of coupled resonators 25 and 27 indicates that for an

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LBO crystal having a length of 15 mm, the spot-sizes
of the fundamental beam at the OPS-structure and in
the doubler crystal are preferably about the same.
This result simplifies the design of the resonator,

5 since it makes it possible to place the doubling
crystal in the proximity of the OPS-structure (as
illustrated in FIG. 5), without having to create, in
the common optical path of resonators 25 and 27, a
tightly-focused waist in which to place optically-

10 nonlinear (doubling) crystal 50. In one preferred
resonator configuration, the fundamental beam has a
spot-size of about 200 μm at OPS-structure 32, a
spot-size of about 200 μm in optically-nonlinear
crystal 50, and a spot-size of about 50 μm in

15 optically-nonlinear crystal 62. The 2H-resonator 27
is designed so that the spot-size of the 2H-beam in
optically-nonlinear crystal 50 is about 150 μm, and
in optically-nonlinear crystal 62 is about 40 μm.

Referring now to FIG. 6, still another

20 embodiment 90 of an OPS-laser in accordance with the
present invention is depicted. Laser 90 includes two
resonators 29 and 31 having a common axial path 37
(indicated in bold line in FIG. 4) over a portion of
their total length. Resonator 29 may be defined as a

25 "fundamental resonator" and is terminated at one end
thereof by mirror 26 and at the other end thereof by
mirror-structure 30 of OPS-structure 32. OPS-
structure 32 is mounted and pumped as described above
for lasers 20, and 60. Only one pump-light-delivery

30 fiber and associated focussing optics are depicted in
FIG. 6, for clarity.

Resonator 31 may be defined as a "second
harmonic resonator". Resonator 31 is terminated at
one end thereof by mirror 74, and at the other end

thereof by a mirror 92. Resonator 31 is folded by a fold-mirror 94. Mirror 28 in this embodiment is coated for maximum reflection at the fundamental-wavelength. Mirror 74 is coated for maximum

5 reflection at the 2H-wavelength. Mirror 92 is coated for maximum reflection at the fundamental, 2H, and, fourth harmonic (4H) wavelengths. Mirror 94 is coated for maximum reflection at the 2H-wavelength and maximum transmission at the 4H-wavelength

10 The axes of the resonators are folded together by dichroic beamsplitters 72 and 73, each thereof coated for maximum reflection at the 2H-wavelength and maximum transmission at the fundamental-wavelength. Accordingly, the common axial-path of

15 the resonators 29 and 31 extends only between beamsplitters 72 and 73. For reasons discussed above, mirror 74 is mounted on a driver 76 controlled by a controller 82 in accordance with power detected by detector 80 to interferometrically-match

20 resonators 29 and 31.

Optically-nonlinear crystal 50 is arranged for frequency-doubling fundamental-radiation circulating along common path 37 of resonators 29 and 31. Frequency-doubled radiation so generated circulates

25 and builds up in resonator 31. Another optically-nonlinear crystal 67 is located in folded portion 31A of resonator 31 between mirrors 92 and 94 thereof. Optically-nonlinear crystal 67 is arranged for frequency-doubling circulating frequency-doubled

30 radiation 2H thereby generating frequency-quadrupled (4H) radiation. The 4H-radiation exits resonator 31 via fold-mirror 94.

Such a resonator configuration is advantageous in the generation of 244 nm radiation through fourth-

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harmonic generation of 976 nm. A preferred
optically-nonlinear (doubling) crystal 50 for this
application is an LBO crystal having a length of
about 15.0 mm, with orientation of the crystal-axes
5 identical to those described above with reference to
laser 20 of FIG. 1. Optically-nonlinear
(quadrupling) crystal 67 is preferably a BBO crystal
having a length of about 8.0 mm. This crystal is
preferably cut for propagation at an angle of 54
10 degrees from the optic-axis, in a plane containing
the optic (Z) axis and making an angle of 30 degrees
with the X-Z crystallographic plane of the optically-
nonlinear crystal.

 The 2H-radiation propagates with polarization
15 perpendicular to the optic axis, (ordinary
polarization) the 4H radiation is generated with
extraordinary polarization (normal to the 2H-
polarization). Preferably mirror 26 has a radius of
curvature of 30 cm., mirror 94 has a radius of
20 curvature of 10 cm, and mirrors 74 and 92 are flat
mirrors.

 Similar considerations apply for the beam spot-
size in optically-nonlinear crystals 50 and 67 as
apply for crystals 50 and 63 of FIG. 5. Numerical
25 simulations indicate that an optimum, relatively
large, beam-size exists for the beams inside the
optically-nonlinear (doubler) crystal 50. The
fundamental-radiation spot-size in optically-
nonlinear (doubler) crystal 50 is preferentially the
30 same as the spot-size at OPS-structure 32, for a
crystal length of about 15 mm. The "second harmonic
resonator" 31 is dimensioned so as to generate a 2H
spot-size in optically-nonlinear crystal 67 equal to
the fundamental beam spot-size divided by the square

root of two (1.414), so that a beam sustained by the resonator 31 has the same transverse size as beam generated by optically-nonlinear crystal 50. The 2H-radiation is focused by concave fold-mirror 94 into

5   the optically-nonlinear crystal 67, to a spot-size of about 50 microns ($1/e^2$ radius).

Another preferred material for optically-nonlinear crystal 67 is cesium lithium borate (CLBO). This material can advantageously substitute BBO for

10   frequency-doubling 488 nm radiation in this and other applications. A CLBO crystal for frequency-doubling 488 nm radiation is preferably cut for propagation of the beam at an angle of 75.7 degrees from the Z-axis, in a plane containing the Z axis and at an angle of

15   45 degrees from the X-Z plane. The 244 nm radiation so generated is polarized in the plane defined by the direction of propagation and the Z-axis (extraordinary polarization), the 488 nm radiation is polarized perpendicular to the 244 nm radiation. The

20   nonlinear-efficiency of CLBO for this application is the same as that of BBO. CLBO, however, has a significant advantage of a five-times-greater angular acceptance than BBO, and a four-times smaller walk-off angle than BBO. A greater acceptance angle

25   and smaller walk-off angle both contribute to increasing the net conversion-efficiency of an optically nonlinear crystal. First order considerations of acceptance angle and walk-off angle indicate that the conversion-efficiency of CLBO may

30   potentially be several times higher than the efficiency of BBO. These first-order considerations are applicable in general to frequency-doubling radiation having a wavelength between about 425 nm and 525 nm in any resonator. The radiation in that

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wavelength range may be the fundamental-radiation or harmonic radiation of any gain-medium.

While embodiments of high-power OPS-lasers in accordance with the present invention are described above with respect to intracavity frequency-multiplication arrangements, it will be evident to one skilled in the art that high-power OPS-laser in accordance with the presentation may be operated, without intracavity optically-nonlinear crystals, simply as an efficient source of high-power single-mode fundamental radiation. A fundamental output power of at least 2 W and even greater than 5 W may be achieved in fundamental resonator embodiments of the an OPS-laser in accordance with the present invention.

By way of example, 10 W of single axial-mode fundamental radiation at 976 nm was generated in an OPS-laser 20F (see FIG. 7) including a simple linear (not folded) resonator 22F formed by a concave output-coupling mirror 28F and mirror structure 30 of OPS-structure 32. Mirror 28F has a radius of curvature of 30 cm and is spaced apart from OPS-structure 32 by a distance of about 15.0 cm. A birefringent filter 52 is preferably included in resonator 22F. This allows for output-wavelength adjustment which may be required if manufacturing tolerances of OPS-structure 32 provide peak gain at some wavelength slightly displaced from a desired output-wavelength.

Such an inventive OPS-laser could be used as a radiation-source for extracavity frequency-multiplication using either a single-pass arrangement of optically-nonlinear crystals or by directing the fundamental-radiation into a prior-art extracavity

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ring-resonator, including, or formed from, an
optically-nonlinear material. A high-power OPS-laser
in accordance with the present invention may also
provide a source of fundamental (pump) radiation for

5   an optical parametric oscillator (OPO), co-linearly
or non-colinearly pumped. Such arrangements are
disclosed in co-pending U.S. Patent Application No.
09/179,022 by the same inventors, the complete
disclosure of which is hereby incorporated by

10   reference.

      Proceeding now with a description of mode-
control and other scaling aspects of the present
invention, a surprising discovery was that single
axial-mode operation of the inventive lasers was

15   simply achieved even at the relatively long
resonator-lengths required for the exemplified high-
power operation. The long resonator length is
required for reasons, inter alia, as follows.

      The gain-structure of an OPS has some inherent

20   limitations due to the need to strongly absorb pump-
light in layers separating the QW layers. These QW
layers are preferably optically-spaced apart by a
half-wavelength of the fundamental radiation. Prior-
art investigations of such structures seem to have

25   resulted in a general belief among practitioners of
the relevant art that a number of about fifteen such
QW layers is about optimum. This results at least
from a consideration that the pump-light, through
absorption in the structure, may not penetrate

30   effectively more than fifteen half-wavelengths deep.
It should be noted here that use of gain-structures
with 15 QW layers in examples of OPS-lasers in
accordance with the present invention should not be
construed as limiting the inventive OPS-lasers or

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indicating that optimization of the depth and QW
content of such gain-structures has reached a limit.
In developing the inventive OPS-lasers, emphasis has
simply been placed, with evident success, at

5 addressing other scaling issues and other structural
issues of OPS-structures. A discussion of such other
issues is set forth below.

Considering, for the purposes of this
description that some limit, whatever it is, to the

10 depth or QW layer content of OPS gain-structures
exists, then another approach to increasing available
gain (accordingly power) in the gain-structure is
necessary. One such approach to increasing output-
power in accordance with the present invention is to

15 increase the pumped-area on the OPS-structure.

In order to take advantage of a larger pumped-
area, however, a resonator must be increased in
length such that the resonator mode-size is
sufficient to extract all of the gain available in

20 the pumped-area. Resonator length is increased in
proportion to the square of the increase in mode
size. Accordingly, with increasing power being
derived, inter alia, from increasing mode size, the
dimensions of the inventive OPS-resonators radically

25 depart from the prior-art compactness which appears
from prior-art teachings to be an attractive feature
of OPS-lasers. Indeed, dimensions of the inventive
OPS-lasers become comparable with the dimensions of
prior-art diode-pumped solid-state (DPSS) laser-

30 resonators of similar output-power and beam-quality.
As will be evident from this description, however,
these inventive resonators, particularly those
arranged for IC frequency-conversion, have certain

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characteristic design features particularly related
to the use of an OPS-structure as a gain-medium.

One originally anticipated problem in
drastically increasing the length of an external OPS-
5   laser resonator is the problem of mode-control,
specifically, operating in a single axial-mode.
Operation in a single axial-mode is preferred, inter
alia, for maximizing and decreasing temporal
fluctuation of output-power. As noted above
10   operating a "fundamental resonator" in a single
axial-mode is particularly preferred in multiple-
resonator IC frequency-multiplication embodiments of
OPS-lasers in accordance with the present invention.

In above-mentioned prior-art DPSS-lasers, as the
15   length of a resonator is increased, the number of
possible axial (longitudinal) modes of oscillation is
also increased, absent any measures for preventing
this. It would also be anticipated, on prima facie
consideration, that this problem would exacerbated in
20   an OPS-laser because of the greater gain-bandwidth of
a semiconductor gain-medium compared with a solid-
state (dopant:host) gain-medium of a DPSS-laser.

Typically, a large number of axial-modes leads
to a fluctuating (noisy) power output as the modes
25   compete chaotically for gain in the gain-medium.
Prior-art measures which have been taken in DPSS-
lasers to limit the number of oscillating modes and
reduce output-noise include selective placement of
the gain-medium in the resonator in positions where
30   phase-relationships between adjacent modes limit this
mode-competition. This approach has met with only
limited success in prior-art DPSS-lasers. It is
believed that, practically, true single mode
operation has only been possible in prior-art lasers

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by mechanically stabilizing the resonator and
including a highly wavelength-selective element in
the resonator, with its attendant problems of
resonator loss, maintenance of tuning, and the like.

5   Surprisingly it has been found that single
axial-mode operation is possible in a high power OPS-
laser in accordance with the present invention
apparently independent of the physical length of the
resonator, at least up the 25 cm length of the above

10   exemplified inventive laser. It is believed that
this length could be significantly further extended,
for example, up to 100 cm or greater, while still
maintaining single-axial-mode operation without any
special provision for providing such operation.

15   It is believed, without being limited to a
particular theory, that this surprising discovery may
be explained as follows. In all above-described
embodiments of the present invention, gain-structure
34 of OPS-structure 32 is located precisely at the

20   end of the "fundamental-resonator", a position in
which all possible axial-modes of operation (standing
waves) have a node, i.e., are exactly in phase.

An OPS gain-structure of the present invention,
is only about seven wavelengths "long". The

25   resonator itself may be tens of thousands or even
hundreds of thousands of wavelengths long.
Accordingly, even widely numerically separated modes
(i.e., N and N$\pm$m where m is an integer) do not become
appreciably out of phase within the gain-medium.

30   Now, the OPS gain-structure, with half-
wavelength-spaced QW layers only provides gain in
narrow region one-half-wavelength apart.
Accordingly, as the actual wavelengths of adjacent
possible modes differ fractionally, at most, by only

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a few millionths of a wavelength, or a few hundredths of the width of the QW layers, all possible modes have about an equal chance to extract the available gain. That mode which begins to oscillate first wins

5   the "mode-competition" and deprives the others of the gain needed to oscillate, thereby forcing single axial-mode operation.

        To ensure true single-mode (single-frequency or TEM_{00}) operation in an OPS-laser in accordance with

10   the present invention, it is preferable to design resonators, wherein, as exemplified above, the pumped-area (pump-spot) and fundamental spot-size at OPS-structure 32 are about the same, *i.e.*, the ratio of pump spot-size to mode-size is about unity (1.0)

15   or less. This provides that there is insufficient gain available outside the TEM_{00} spot-size to support other transverse-modes of oscillation of different frequencies while still deriving maximum gain from the pumped area.

20   Above-described OPS-lasers in accordance with the present invention have been described in terms of having physically long resonators, it being understood here, that what is referred to as resonator-length is the axial-length or distance

25   between resonator end-mirrors. One skilled in the art, however, will recognize that increasing the physical resonator length is not the only way to provide for a large mode-size in the gain-structure 34 of OPS-structure 32 for increasing power.

30   Incorporating a suitable optical system within a resonator can produce a large "equivalent length" for the resonator, even when the actual (physical) length of the resonator is relatively short. This may be used to provide a large spot-size at an OPS-structure

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in accordance with the present invention with a
resonator having a relatively short physical length.
An example of such a resonator arrangement used in a
prior-art, flashlamp-pumped Nd:YAG laser, employing a
5   telescopic arrangement of lenses in the resonator, is
described in a paper by Hanna et al., Opt. Quantum
Electron. 13, 493 (1981).

        Ray optics considerations indicate, however,
that in any such complex resonator, wherein a mirror-
10   structure 30 of an OPS-structure 32 forms at one
extremity of the resonator, the complex resonator is
equivalent (as seen from mirror-structure 30) to a
simple resonator consisting of a mirror (generally
curved) placed at a specific distance from mirror-
15   structure 30 of the OPS-structure 32. In other
words, any arbitrarily complex resonator can always
be reduced, for the purpose of determining mode-size
at gain-structure 34 of OPS-structure 32, to an
equivalent simple resonator having mirror-structure
20   30 of OPS-structure 32 at one end thereof, and a
curved mirror at the other end thereof. Accordingly,
in long-resonator-type OPS-lasers in accordance with
the present invention there can be defined an
equivalent or optical resonator-length necessary to
25   provide a desired mode-size at OPS-structure 32.
This optical length definition encompasses the
relatively simple resonator structures described
above, wherein the optical length is close to the
physical length as well as any more complex
30   arrangements for shortening physical length while
maintaining a sufficiently large optical length. A
preferred optical length for the resonator of an OPS-
laser in accordance with the present invention is at

least about 5 cm and preferably greater than about 10 cm.

The most straightforward way to increase the mode or spot-size at an OPS-structure 32 in an OPS-laser in accordance with the present invention is to increase the optical length of the resonator by simply increasing the physical length of the resonator, with an appropriate choice of the radius of curvature of resonator mirrors. The beam spot-size required for the generation of multi-watt radiation in the above-exemplified laser 20 of FIG. 1 was obtained by employing a resonator length of 25 cm, which, even though much larger than resonator lengths of prior art OPS-lasers, is still small enough to allow for convenient packaging of the laser while still allowing operation in a single axial-mode.

Turning next to thermal management issues, as discussed briefly above, thermal-management of OPS-structure 32 in an OPS-laser in accordance with the present invention is particularly important. Accordingly, a discussion of some important aspects of the thermal management is set forth below with reference to FIG. 8. FIG. 8 depicts, in detail, OPS-structure 32 and heat-sink 36 on which it is bonded.

The thermal-management problem may be summarily defined as follows. Pump-light 42 is absorbed in gain-structure of OPS-structure 32. That portion of the absorbed pump-light which does not generate electrical-carriers, *i.e.*, does not provide laser-radiation, generates heat in gain-structure 34. This heat must be conducted away by heat-sink 36 at a rate sufficient to keep the temperature of gain-structure preferably below a temperature of about 90°C. It

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should be noted here that this temperature is merely provided for guidance and should not be considered critical or limiting.

5   Mirror-structure 30 impedes the conduction of heat from gain-structure 32 to heat-sink 36. As discussed above, in a preferred, inventive heat-sink arrangement, OPS-structure 32 is bonded, by a solder layer 110, to a layer 112 of synthetic diamond, preferably having a thickness of about 0.3 mm.

10   Diamond-layer 112, in turn is bonded, by another solder layer 114, to a copper-bodied microchannel-cooler 116.

In developing a heat-sink configuration for OPS-structure in accordance with the present invention,

15   consideration was first given to the heat-sink properties of massive substrates of copper and diamond. From calculations considering the pump-power density provided by the above exemplified 34 W of pump-power delivered directly on the surface of a

20   massive (essentially infinite in extent) copper heat-sink it was estimated that surface temperature on such a heat-sink would be 110°C. In practice, the 34 W of pump power would not be delivered directly to the surface but would be impeded by the materials of

25   mirror-structure 30. These materials have a relatively low thermal-conductivity. Accordingly, the temperature of gain-structure 34 could be expected to be about 15°C higher than the highest temperature at the surface of the heat-sink.

30   From calculations considering the pump-power density provided by the above exemplified 34 W of pumping delivered directly on the surface of a massive CVD-diamond (having a thermal-conductivity 2.5 times higher than copper) heat-sink, it was

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estimated that the surface temperature on such a heat-sink would be 45°C. This would be a tolerable temperature for gain-structure 34 of OPS-structure 32. However, a diamond (even synthetic) sufficiently

5 large to be considered of infinite extent would be prohibitively expensive, if at all obtainable.

Giving consideration to a microchannel-cooler, it was determined that the surface temperature on such a cooler provided by the above exemplified 34 W

10 of pumping delivered directly thereto would be about 110°C. It was then determined that if a relatively thin layer of synthetic diamond were bonded to the same microchannel-cooler, the surface temperature (on the diamond layer) would be only 55°C degrees, *i.e.*,

15 comparable with the calculated temperature for the above-discussed hypothetical massive diamond heat-sink. This determination was significant in enabling the pump-power densities required for OPS-lasers in accordance with the present invention to be safely

20 delivered to OPS-structure 32.

On a prima facie consideration, it may appear that at a constant pump-power density, the above-exemplified temperatures in OPS-structure 32 may be expected to be remain the same as the pumped-area

25 thereon is increased, making power-scaling beyond the above identified levels merely a matter of increasing resonator length. On closer investigation, however, this proves not to be the case.

By way of illustration of the pumped-area

30 scaling problem, FIGS 9 and 10 depict computed isothermal contours (assuming radial symmetry) in respectively a relatively-massive (1.0 mm-thick) copper heat-sink and in a 0.3 mm-thick CVD-diamond layer bonded on a 0.7 mm-thick copper-heat-sink. The

isothermal contours represent response to a uniform surface heating at a rate Q of 180 Watts per square mm (W/mm^2) within a circle H of 0.25 mm radius. (corresponding to the above-exemplified pump-power

5   density on OPS-structure 32). Isothermal contours are at 5°C intervals. The terminology "relatively massive", as used above, means in relationship to the dimensions of OPS-structure 32.

It can be seen from both FIGS 9 and 10 that the

10   temperature rises from edge to center of the heated (pumped) area. Increasing the pumped-area at the same pump-power density, accordingly, would increase the peak temperature of the OPS-structure. Fortunately, however, this increase is proportional

15   to the square-root of the increase in area. This allows some trade-off between pump-power density and increasing pumped-area.

The effectiveness of the CVD-diamond layer, of course is also evidenced by the lower peak

20   temperature of between 45°C and 50°C achieved with the diamond layer (see FIG. 10) compared with a peak temperature of about 100°C without the CVD-diamond layer (see FIG. 9).

Synthetic diamond in single crystal form has

25   twice the thermal-conductivity of the CVD form. Accordingly, by substituting a single crystal diamond layer for the CVD-diamond layer a further surface temperature reduction of about 20°C could be expected. Synthetic diamond in CVD and single

30   crystal form is available from Sumitomo Electric Industries (USA) Ltd, of New York, New York.

The high thermal-conductivity of the above discussed inventive arrangement of heat-sink 36 ensures not only low temperature in gain-structure 34

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of OPS structure 32, but also low transverse
temperature gradients in the plane of the OPS-
structure. Transverse temperature gradients cause,
through temperature dependence of the index of

5   refraction of the OPS material, transverse variation
of the optical path seen by the fundamental-radiation
on propagation in the OPS-structure. Such gradients
manifest themselves in a solid-state gain medium as
"thermal-lensing" which means that the gain-medium

10 behaves, in a first order approximation, as a
positive spherical lens. This phenomenon is well
known in prior-art DPSS lasers, and complicates the
design of resonators for such lasers, as these
resonator designs must take into account both the

15 thermal-lensing and its variation as the pump-power
level is changed. By way of example, a typical
neodymium-doped yttrium vanadate ($Nd:YVO_4$) gain-medium
crystal can exhibit thermal-lensing as high as seven
diopters under typical pump conditions.

20   In considering the design of heat-sink 36 it was
recognized that careful design could lead to
exceptionally low values for the thermal-lensing in
an OPS-laser in accordance with the present invention
compared with values encountered in prior-art DPSS

25 lasers. By way of example, in the above-described
example of laser 20 (FIG. 1), employing a CVD diamond
layer on a microchannel cooler as a heatsink, a
thermal lensing of significantly less than one
diopter was measured. The use of synthetic,

30 single-crystal diamond instead of CVD diamond would
reduce this already small thermal lensing by a factor
of two. Such low thermal-lensing simplifies
considerably the design of the laser resonator.
Generally, in designing a resonator for an OPS-laser

in accordance with the present invention, it may be assumed that there is will be no thermal lensing.

Turning now to the heat-transfer-impeding effect of mirror-structure 30 of OPS-structure 32, in the

5 example of the inventive OPS-laser discussed above, the total thickness of mirror-structure 30 of OPS-structure 32 is about 4.1 μm. Computations, based on this total thickness; bulk thermal-conductivity values of GaAs and AlAsP; and the structure of

10 cooled-substrate 36 as depicted in FIG. 6, indicated that because of the heat-transfer-impeding effect of mirror-structure 30., the temperature of gain-structure 34 would be between about 18°C and 20°C higher than would be the case, were the gain-

15 structure directly-bonded to diamond layer 112 of cooled-substrate 36. Accordingly, a substantial portion of the potential reduction in surface temperature offered by the bonded diamond layer is sacrificed to the mirror-structure. From

20 experimental observations of the shift of the fluorescence spectrum of gain-structure 34 under the operating conditions of the above described practical example of inventive OPS-laser, it has been determined that gain-structure 34 is at a temperature

25 of about 90°C.

It is clear, that an improvement in the thermal-conductivity of mirror-structure 30 of OPS-structure 32 could allow a higher pump-power to be delivered to gain-structure 32. This would allow further

30 increases in output-power. Some approaches to improving this thermal-conductivity are set forth below.

An advantage of growing OPS-structure 32 in the manner described above is that it is neither

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necessary that mirror-structure 32 be epitaxially-grown, nor necessary that it be formed entirely, if at all, from semiconductor materials. Given this flexibility, it is possible to design mirror-

5   structures 30 of OPS-structures 32 in accordance with the present invention using a wide selection of materials for forming high and low refractive index layers. Accordingly, values of absolute refractive index of the materials, and thermal-conductivity of

10   the materials, can be selected such that such that the thermal-conductivity in the axial direction of the mirror-structure (as a whole) is maximized. Clearly, of course, the materials selected must have minimal absorption (be highly transparent) for the

15   fundamental-wavelength such that mirror-structure is capable of providing maximum reflectivity for the fundamental-wavelength. Maximum reflectivity in this regard may be defined as a value preferably about 99.9 percent or greater.

20   One option for increasing thermal-conductivity of mirror-structure 30 is to substitute a layer of a highly reflective metal such as aluminum, silver, gold, copper or magnesium, for several high and low refractive index layer-pairs of transparent

25   materials, and to allow an absorption in the metal layer of about 0.1 percent. Dielectric multilayer overcoated aluminum mirrors of similar structure, for providing inexpensive high-efficiency reflectors for optical scanners, copiers and the like, are often

30   referred to in the optical-coating art as "enhanced metal-mirrors".

A metal layer in a mirror-structure 30 in accordance with the present invention would be the last-deposited (mirror) layer and would be furthest

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from the gain-structure. As this metal layer, in a completed OPS-structure 32, would be in direct contact with the heat-sink, it is believed that at least 0.1 percent absorption would be tolerable.

By way of example, using the GaAs and AlAsP materials exemplified above, with a 1000 Å layer of gold as the final layer, 99.9% reflectivity could be provided by a structure having only nine pairs of GaAs and AlAsP layers . Such a structure would have a total thickness of only about 1.47 μm, i.e., about one-third the thickness of the mirror-structure of the above-described example. Accordingly up to a three-fold increase in thermal-conductivity of the mirror-structure as a whole can be anticipated.

It is believed that further reductions in thickness could be possibly be obtained by using a material having a much lower refractive index than AlAsP as a low refractive index material, for example, barium fluoride (BaF_2) having a refractive index of about 1.48. Using a 1000 Å-thick layer of gold as a final layer, 99.9% reflectivity could be provided by a mirror-structure 30 having as few as two pairs of GaAs and BaF_2 layers. Such a mirror-structure would have a total thickness of only about 0.54 μm, i.e., about one-eighth the thickness of the OPS-structure of the above described example. What is gained in thermal-conductivity by the total thickness reduction, however, will be at least partially offset by the lower conductivity of BaF_2 compared with AlAsP and the greater physical thickness of BaF_2 required to provide one-quarter wavelength optical thickness at the fundamental-wavelength.

Such "enhanced metal-mirrors" may be particularly useful in OPS-structures which have fundamental emission at wavelengths shorter than about 0.7 μm where semiconductor materials have too

5　great an absorption to be used effectively in multilayer reflectors. For these wavelengths, use must be made of dielectric materials such as titanium oxide (TiO_2) and niobium oxide (Nb_2O_5) to provide high index layers, in combination with materials such as

10　silicon dioxide (SiO_2) as a low index layer. It is useful to note that a mirror using only a combination of TiO_2 and SiO_2 layers, having the same reflectivity as a mirror made from only GaAs and AlAsP layers, would have a total thickness about fifty percent

15　greater.

It should be noted that, depending on the selection of a highly reflecting metal for an "enhanced-metal" type mirror-structure, and the type of bonding material selected for bonding the OPS-

20　structure to heat-sink 36, it may be necessary to add a layer, preferably of a suitable metal, on the reflective metal layer to prevent that layer from reacting, alloying or dissolving in the bonding material. As this additional layer, would be (as far

25　as incident laser radiation is concerned) "behind" the reflective metal layer it is not important that it be highly reflecting.

As discussed above, OPS-structures such as OPS-structure 32 are grown over essentially the entire

30　area of a semiconductor wafer. After the OPS-structure is grown, the wafer is diced into chips of OPS-structure. A prior-art-preferred dicing method involves scribing and breaking the wafer to form the chips. Breakage takes place, cleanly and smoothly,

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along a crystalline plane of the wafer and the
epitaxially grown OPS-structure thereon. Referring
now to FIG. 11, an OPS-structure chip (designated
here, for consistency by reference numeral 32) formed
as described above, has what may be termed as an
emission face 119 on gain-structure 34 and has smooth
end-faces 120 in resulting from the scribe-and-break
dicing method. End faces 120 are at right angle to
emission-face 119 and have a relatively-high Fresnel
reflectivity (about 30%) due to the relatively-high
refractive index of semiconductor materials of the
gain-structure. At operating powers contemplated for
OPS-lasers in accordance with the present invention,
absent any preventive arrangements, laser action can
take place laterally (indicated in FIG. 11 by arrows
B) in resonators formed by parallel pairs of end-
faces 120.

During operation, such parasitic lateral
oscillation would rob gain-structure 34 of OPS-
structure 32 of gain which would otherwise be
available for providing laser-action in the intended,
surface-emitting direction (indicated in FIG. 11 by
arrows C). Certain measures may be taken to suppress
such parasitic lateral oscillation. One such measure
comprises employing a dicing method wherein the wafer
is cut or scribed completely from one side to the
other with a diamond-scribe, diamond-saw, or like
abrasive-cutting device. Following such scribing,
end-faces 120 will be sufficiently rough or irregular
that they are ineffective as mirrors. Accordingly,
parasitic lateral oscillation will effectively
suppressed. Other methods of roughening the end
faces are not precluded.

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    If end-faces 120 are left smooth as a result of
scribe-and-break dicing, coating the end-faces with a
simple antireflection coating of material having a
lower refractive index than the end-faces, such as
5   aluminum oxide (Al_2O_3) or yttrium oxide (Y_2O_3), can
reduce the reflectivity of end-faces 120 to a level
where they no longer are effective as mirrors,
thereby effectively suppressing parasitic lateral
oscillation.

10   Yet another means of suppressing parasitic
lateral oscillation is to ensure that the longest
linear dimension (end-face length) of chip 32 (OPS-
structure 32) is significantly larger than the
pumped-area 122. At power levels contemplated for
15   OPS-lasers in accordance with the present invention,
the length of an end-face 120 is preferably greater
than about three-times the diameter of the pumped
area. Intrinsic absorption of the unpumped OPS-
structure materials and the increased distance
20   required for radiation to travel between end-faces
120 can provide sufficient loss to effectively
suppress parasitic lateral oscillation even if end-
face 120 are smooth.

    Deliberately increasing absorption of the
25   materials of gain-structure 34 outside the pumped
area for suppressing parasitic lateral oscillation is
not without the bounds of possibility. This may be
accomplished, for example, after growth of OPS-
structure 32, by selective doping or ion
30   implantation. Clearly, any of the above-described
measures for reducing parasitic lateral oscillation
may be use alone or, where appropriate, in
combination.

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Turning now to selection of frequency-conversion materials for OPS-lasers in accordance with the present invention, as noted above, the range of wavelengths available from external cavity OPS-lasers

5   may be extended by frequency multiplication, doubling or mixing. This is preferably accomplished by intracavity (IC) frequency-conversion (harmonic generation), in which an optically-nonlinear crystal is included in a resonator formed between the mirror-

10   structure of an OPS-structure and a (external to the structure) conventional mirror. A particularly preferred optically-nonlinear crystal material for IC frequency converted OPS-lasers in accordance with the present invention is LBO.

15   Because of the limited power available in prior-art OPS-lasers, it has been the practice in such lasers to use an optically-nonlinear material with as high a frequency conversion-efficiency as possible, typically, $KNbO_3$. $KNbO_3$, however, has certain

20   disadvantageous properties that make it a less-than-ideal choice for use in a high-power frequency-doubled laser in accordance with the present invention. These disadvantageous features are a certain fragility, and a limited spectral-acceptance

25   range. The spectral-acceptance range of an optically-nonlinear material is that range of wavelengths which would be frequency-converted for a crystal of the material.

FIG. 12 depicts the computed, normalized

30   spectral-acceptance of $KNbO_3$, and of the significantly-more-durable, but less efficient, LBO. Each is assumed to be in the form of a 5 mm-long crystal. Also depicted is the gain-bandwidth of active layers of InGaAs having a composition selected

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to provide laser action around 97.6 nm. It can be seen that the spectral-acceptance of the $KNbO_3$ is about one-tenth that of the LBO, and is very narrow by comparison with the gain-bandwidth of the active

5 layers.

Now, as the frequency-doubling mechanism of an intracavity optically-nonlinear crystal represents a loss for the fundamental-wavelength, absent any other constraint, the resonator will tend to shift (hop)

10 its oscillation wavelength to a wavelength where there is no loss. When this happens, frequency-doubled output will drop catastrophically, if not cease altogether, and fundamental power will surge correspondingly.

15 Wavelength-hopping will result in a very noisy frequency-converted output of lower average power than would be the case in the absence of wavelength-hopping. This wavelength-hopping can be limited by including in the resonator a highly wavelength-

20 selective element such as a birefringent filter, an etalon, or the like. Any such device having the necessary selectivity, however, would introduce significant resonator losses, thereby limiting output-power. Either way, this would mean that the

25 nominally high conversion-efficiency of the $KNbO_3$ may not be realized, in practice, in its full measure. Further, the wavelength-selective device would probably require an active measure such as temperature control to satisfactorily stabilize its

30 peak-transmission wavelength.

The LBO material, having the much wider acceptance would still not be completely immune from wavelength-hopping, without the wavelength-restraining benefit of an intracavity wavelength-

selective device. Such a wavelength-selective device in the case of LBO, however, can be ten-times less selective than would be required for the $KNbO_3$; would not require active stabilization; and would not

5   introduce significant cavity losses.

For completeness, it is pointed out here that the spectral-acceptance of an optically-nonlinear crystal is inversely proportional to the length of the crystal. The second-harmonic-generating (SHG)

10   efficiency of such a crystal is roughly proportional to the square of a material constant d_{eff}, multiplied by the square of the length of the crystal. As the value of d_{eff} for $KNbO_3$ is about ten-times greater than the value of d_{eff} for LBO, then, in theory at least, a

15   0.5 mm-long $KNbO_3$ crystal would have the same peak SHG-efficiency and spectral-acceptance as a 5.0 mm-long LBO crystal. It is believed, however, that because of the fragility of the KNbO3, a 0.5 mm long KNbO3 crystal may be somewhat impractical to

20   fabricate and handle. The use of KNbO3 crystals in resonators in OPS-laser resonators in accordance with the present invention, however, is not precluded.

Generally, for reasons discussed, above LBO and chromium lithium triborate (CLBO) are preferred for

25   frequency-doubling and, alternatively, for frequency tripling. BBO is preferred for frequency quadrupling and, alternatively, for frequency tripling. For doubling or tripling wavelengths shorter than about 670 nm, optically nonlinear materials including

30   strontium barium borate (SBBO), strontium borate (SBO), and barium zinc borate (BZBO) are believed to be effective. These optically-nonlinear material preferences should not, however, be considered as

limiting IC frequency-converted lasers in accordance
with the present invention.

TABLE 1

Bragg Mirror	QW/Separator	Substrate	Fundamental Wavelength (nm)
1	$In_xGa_{1-x}As/GaAs_yP_{1-y}$	GaAs	900 - 1050
2	$In_xGa_{1-x}P/In_yGa_{1-y}As_zP_{1-z}$	GaAs	700 - 900
3	$InAs_xP_{1-x}/InGa_yP_{1-y}$	InP	930 - 1800

TABLE 2

Structure Number	Bragg Mirror Materials	
	High Refractive-Index Layers	Low Refractive-Index Layers
1	GaAs	$AlAs_xP_{1-x}$
2	$In_xAl_{1-x}P$	$Al_yGa_{1-y}As$
3	Dielectric	Dielectric

Continuing now with a description of preferred
materials for high-power OPS-structures in accordance
with the present invention, TABLE 1 lists preferred
QW layer and separator-layer materials for gain-
structure 30. Each set of materials is associated
with a particular mirror-structure 30 (Bragg mirror)
number, substrate and fundamental-wavelength range.
Details of Bragg mirror, composition are given in
TABLE 2.

The structures represented in TABLES 1 and 2
represent a departure from prior-art-preferred

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structures for the same wavelength ranges, in regard
to both mirror-structures and gain-structures. In
TABLES 1 and 2 compound composition proportions
(subscripts) x, y, and z all have a value between 0.0
5   and 1.0. In each case, materials (compounds) are
selected such that the stress of the OPS-structure as
a whole is as low as practically possible, by
ensuring that the stress-thickness product of all
tensile strained layers and all compressive strained
10   layers is about of equal magnitude. This is of
particular importance in OPS-structures in accordance
with the present invention which are subject to the
stress of high operating temperatures, and
correspondingly large temperature-cycles between
15   periods of operation and inactivity.

The OPS-structure (see FIG. 2) of the above-
exemplified IC frequency-doubled OPS-laser in
accordance with the present invention is an example
of the first-listed family of structures wherein GaAs
20   "transition" layers between the QW and separator
layers, alleviate the stress-difference which would
otherwise exist between these layers. The gain-
structure of the OPS-structure of FIG. 2 can be
generally categorized as being formed from components
25   of the III-V quaternary system InGaAsP wherein the
substrate material is a binary III-V compound of the
components (here GaAs), and wherein the QW layers are
formed from a one possible ternary III-V compound
including both components of the substrate material,
30   and the separator layers are formed from the other
possible ternary III-V compound including both
components of the substrate material. Type 3
structures of TABLE 1 (on InP substrate material)
also fall into this category. This is believed to

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provide the optimum stress compensation for OPS structures formed from this quaternary system. For type 3 structures of Table 1 a mirror-structure including dielectric materials is preferable. One preferred structure includes high refractive index layers of zinc selenide (ZnSe) and low refractive index layers of aluminum oxide. This combination provides about the same reflectivity per number of layer-pairs as the combination of TiO_2 and SiO_2 used in general coating applications in the prior-art, but with a lower total physical thickness and higher thermal conductivity. It is emphasized here that the mirror structures of TABLE 2 are preferred structures for use with QW/separator structures of TABLE 1, the use of other mirror structures with the QW/separator structures of TABLE 1 in OPS-lasers in accordance with the present invention is not precluded.

Further, from the description of inventive OPS-lasers provided above, those skilled in the art may select other OPS-structures for providing fundamental-radiation at wavelengths between about 425 nm and 1800 nm without departing from the spirit and scope of the present invention. Such structures may include, by way of example, QW or active layers selected from a group of semiconductor compounds consisting of, $In_xGa_{1-x}As_yP_{1-y}$, $Al_xGa_{1-x}As_yP_{1-y}$, and $In_xGa_{1-x}N$ where $0.0 \leq x \leq 1.0$ and $0 \leq y \leq 1$. This list, however, should not be considered as limiting the present invention. Second, third and fourth harmonic wavelengths, of course, would be between about 212 and 900 nm; 142 and 600 nm; and 106 and 225 nm. Performance in the shorter wavelength half of the latter range may be somewhat limited by the availability of suitable optical materials.

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Turning next to a discussion of further aspects of increasing output-power in OPS-lasers in the present invention, in embodiments of OPS-lasers described above, only one OPS-structure 32 is

5   included.   Several approaches to increasing output-power to beyond the levels achieved or confidently predicted have been discussed without regard to this. It will be evident to one skilled in the art from these discussions, however, that exploiting the

10   above-discussed approaches alone may lead to a point of diminishing returns.   Should this prove to be the case, or simply as an alternative, output-power (fundamental or harmonic) may be increased by incorporating at least a second OPS-structure in a

15   suitably-configured resonator.   A description of one such resonator is set forth below.

Referring to FIG. 13, a further embodiment 128 of an IC frequency-doubled OPS-laser in accordance with the present invention is depicted.   Laser 128

20   comprises a tightly-folded resonator 130 including two OPS-structures, 32 and 32X.   Resonator 130 is terminated at one end thereof by mirror-structure 30 of OPS-structure 32 and at the other end thereof by a mirror 28.   Resonator 130 includes a birefringent

25   filter 52 for reasons discussed above.   The OPS-structures are mounted on above-described heat-sink assemblies 36.   Resonator axis 132 is folded once by mirror-structure 30X of OPS-structure 32X, and again by a fold-mirror 26.   An optically-nonlinear crystal

30   50, arranged for frequency-doubling, is located in arm 130A of resonator 130, i.e., between fold-mirror 26 and end mirror 28.   Mirror 28 is coated for maximum reflectivity at the fundamental-wavelength. Mirror 26 is coated for maximum reflectivity at the

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fundamental-wavelength and maximum transmission at the 2H-wavelength.

It should be noted here that the tight folding of the resonator is selected to maintain as close to normal incidence as possible on OPS-structure 32X. This is to minimize interference in gain structure 34X between counterpropagating fundamental beams. Such interference can lead to the formation of interference-fringes (a sort of "lateral spatial hole-burning") in the plane of the QW layers, thereby limiting gain extraction from these layers. In this regard, it is also preferable to adjust spacing of the QW layers in gain-structure 34X and the thickness of layers of mirror-structure 30X to compensate for the effective refractive index change due to non-normal incidence, thereby maintaining effective half-wavelength spacing of the QW layers.

Continuing with reference to FIG. 13, a further difference between laser 128 and other above described OPS-lasers in accordance with the present invention is the manner in which pump-light is delivered to the OPS-structures. In laser 128, pump-light is transported along fibers 40 as in other above-described embodiments. Fold-mirror 44 and focusing-lenses 46 and 48 of these other embodiments, however, are replaced with an assembly of two radial-gradient-index lenses 146 and 148. Such lenses are often referred to generically as "selfoc". It has been found such lenses can provide the same optical performance as lenses 46 and 48 in the above-described example of laser 20. In one example lens 146 is a Part No. 06LGS216 available from Melles Griot Inc of Irvine California. Lens 148 is a Part No. SLW180-020-083-A2. This selfoc lens arrangement

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provides convenient access for multi-fiber (fiber-
bundle) pumping in the case of tightly-folded
resonators such as resonator 28. The arrangement may
be used in any other above-described embodiment

5   simply to reduce the volume of pump-light delivery
optics or to permit power to be delivered by more
fibers than would be possible because of the bulk of
the conventional focusing-optics.

    From the foregoing description, those skilled in

10   the art to which the present invention pertains may
devise OPS-lasers including more than two OPS-
structures without departing from the spirit and
scope of the present invention. Such OPS-lasers may
be configured for delivering output-radiation at the

15   fundamental wavelength of the OPS-structures or at
harmonic wavelengths thereof.

    From the description of laser 128 it will also be
evident to those skilled in the art that a folded
laser-resonator may be formed between two external

20   mirrors, and include one or more OPS-structures 32
only as fold mirrors. Such a folded laser-resonator
is depicted in FIG. 14. Here, an OPS-laser 140 in
accordance with the present invention includes a
laser-resonator 142 terminated by mirrors 28F and 144

25   and tightly-folded (for reasons discussed above) by
mirror structure 30 of OPS-structure 32. Heat-sink
and optical-pumping arrangements are the same as
described above for laser 128. Laser resonator
optionally includes a birefringent filter 52.

30   The laser-resonator arrangement of laser 140 may
be useful if it desired to configure a laser-
resonator which is terminated by two non-flat
mirrors. It will be evident from the arrangement of
laser 140 that similar arrangements wherein a

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resonator is not terminated at one end thereof by a mirror-structure of an OPS-structure may be devised for any other above described embodiments of OPS-lasers in accordance with the present invention.

In summary, several embodiments of high-power, IC frequency-converted, OPS-lasers in the accordance with the present invention have been described above. Generally, embodiments of the inventive laser can generate second, third or fourth harmonic output-power from fundamental radiation at a power of 100 mW or greater, and even at 1 W or greater. These high-harmonic output powers can be achieved in single axial mode or TEM_{00} operation with a beam-quality of less than about twice the diffraction-limit. Particularly notable is the ability of the inventive lasers to generate UV output-radiation at these high output-powers, more particularly, at better than one percent pump-to-harmonic efficiency by second-harmonic generation from fundamental radiation in a 700 nm to 800 nm wavelength ranges.

The inventive OPS-lasers, can provide a means of generating wavelengths, in a true CW mode of operation, which can closely match the optimum wavelength for many laser applications, in fields such as medicine, optical metrology, spectroscopy, optical lithography, and precision laser machining. By way of example, an inventive OPS laser can efficiently produce CW output radiation in the 590 to 600 nm wavelength range by second-harmonic generation from an OPS-structure emitting in the 1180 to 1200 nm range. 590 to 600 nm is advantageous for ophthalmic surgical application. This wavelength range can not be efficiently generated by prior-art lasers. The ability to generate high-power UV radiation is

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applicable in particular in areas such as direct writing or patterning of printed circuit boards or conventional UV plates. In such applications the inventive OPS-lasers offer not only power, efficiency

5 and beam quality, but also the ability for many applications to "tailor" an output wavelength to an absorption-peak of material to be exposed, cut, ablated, heated, photochemically altered or otherwise treated, thereby reducing the absolute power required

10 for the applications. From the above presented description of the OPS lasers those skilled in the appropriate arts may conceive many other uses for the inventive lasers without departing from the spirit and scope of the present invention.

15 The present invention is described and depicted herein with reference to a preferred and other embodiments. The present invention is not restricted, however, to those embodiments described and depicted. Rather, the invention is limited only

20 by the claims appended hereto.

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